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Personal Area Technologies for Internetworked Services



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Abstract

This article reviews wireless enabling technologies to support interworking of heterogeneous networks, and covers two relevant topics; personal area networks and multistandard terminals. The variability of the PAN channel is demonstrated, and the implications for air interface design are discussed. To ensure effective operation in shared spectrum, radio resource management and medium access control strategies for PANs are also discussed. It is recognized that terminal cost has significant implications for user acceptance; therefore, by combining functionality from different standards (cellular, wireless LAN, broadcast), cost can be reduced. Technologies and architectures relevant for multistandard terminals are reviewed, including synchronization and linear RF processing. Finally, the potential for further simplifications within the framework of multicarrier CDMA is considered.

Introduction

What is beyond third generation (3G)? To some it is new high-data-rate air interfaces, to others it is a network of networks that focuses on greater transparency of the different network capabilities to the user. This article takes the latter view, where personal area network (PAN) technologies play an increasingly important role of binding together different local and wide area networks in order to maximize the services available to the user [1, 2].

The business case suggests that the different networks (cellular, broadcast, wireless local area network — WLAN) will on the whole remain distinct, with operators not willing to relinquish control of their own network, although willing to support the user being more flexible in their choice of which network to use. This choice will be based on factors including user requirements and preferences; the networks available to the user; network quality of service (QoS); and cost to carry the data. Furthermore, the degrees of freedom available will change depending on the user's location, his/her purpose (work or pleasure), and network loading. Therefore, distinct from integration of networks, which implies a transfer of network control, this article focuses on interworking of networks. Rather than requiring a transfer of control between networks, the concept being considered implies a greater level of choice for users on how their data is transported.

A number of initiatives are underway to investigate how different networks can work together, such as digital video broadcast-Universal Mobile Telecommunications System

(DVB-UMTS)¹ and 3G-WLAN interworking [3]. However, these are focused on specific standards. While some multi-standard systems are becoming more available, the framework to allow the *user* to choose over which network an application is delivered does not commonly exist. Furthermore, applications tend to be tied to a single network, and when that network is no longer available the user loses access to the associated services and application. The research program described here (part of the Virtual Center of Excellence in Mobile and Personal Communications,² Mobile VCE) is taking a more generic approach such that the solution is more widely applicable and easily adopted by future standards, subject to a limited set of requirements.

In the user's personal space, a number of devices will coexist and need to communicate. This requirement is met by the PAN concept using wireless connectivity between devices. This is important because users will be able to choose the devices they wish to own, and can change their configuration according to their needs. In the short term this means choosing which devices to carry, or longer term which to buy, such as new network devices for cellular, broadcast, WLAN; new man-machine interfaces (e.g., keyboards); headphones and displays; or personal devices such as an MP3 player or a personal digital assistant (PDA). A PAN is typically considered as covering short ranges on the order of 10 m. In many contexts the term PAN is used to describe technologies used for cable replacements between local devices. Within the program under discussion here, the focus is on user-worn or -held devices, so the term *body area network* (BAN) may be more appropriate. Consequently, the design of PAN technologies around and between bodies is of primary concern. Furthermore, these devices must be low-cost and low-power but also support high data rates.

In order for interworking of networks to become a reality, three work areas have been identified by the Mobile VCE. The scope of the three work areas are:

- **Wireless enablers** (WE) — Developing physical and data link protocol layer technologies for PANs and multimode terminals. Preliminary outputs from this work area are described in this article.
- **Personal distributed environment** (PDE) — Developing the tools to manage the user's environment, such as feature and service discovery, managing user profiles, and mapping user data requirements onto network resources. The PDE offers users the ability to access services from different sources and under different conditions in a transparent way.

¹ <http://www.dvb.org/index.php?id=87>

² <http://www.mobilevce.com>

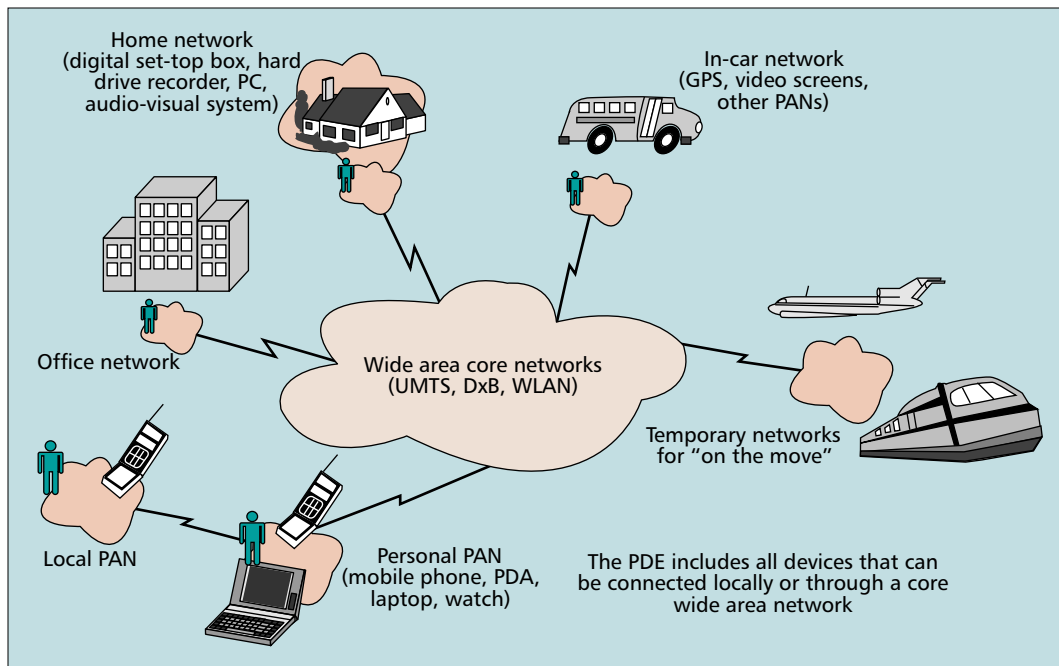


FIGURE 1. The PDE concept.

- **Interworking of networks (IoN)** — Managing the interface between networks to support interworking, to the mutual benefit of all network operators and the user.

While the PAN forms the connection between devices in the local area, the scope of the PDE extends to remote devices using external data delivery mechanisms (cellular, broadcast, WLAN) through gateway devices. A representation of the PDE is given in Fig. 1.

The structure of this article is as follows. We take a user-centric view and describe the user scenarios that can be potentially supported through the concept of interworking of networks. We will review the role of the PAN and the new requirements placed on PAN technologies. An overview of specific issues such as BAN channel characteristics, radio resource management, and interference mitigation techniques for PANs is given. We then review the work on multimode terminal architectures and technologies for PAN gateway devices. Finally, conclusions are given and future work topics identified.

Interworking Scenarios and Implications

To increase the likelihood of a new system concept becoming commercially viable, the needs of the user must be the focal point in terms of efficient and effective service delivery. The Mobile VCE has pioneered a number of scenarios that demonstrate situations in which the interworking of networks becomes a necessary extension to existing network behavior. The scenarios describe attributes such as devices in the PDE (only some of which may be in the local PAN), physical environment, user mobility, and the applications used. Table 1 lists some of these scenarios. A further stage of analysis has been carried out to identify the particular requirements within each scenario that are of most interest to each work area (WE, PDE, IoN). For wireless enablers, the requirements of primary interest are aspects such as data capacity, latency, and acceptable error performance. Table 1 also includes this analysis for the local PAN of each scenario.

It is clear that the range of capabilities arising from these

Scenario	PAN devices	Environment	Mobility	Applications	Max. data rates	Latency issues
Pickwick	PDA, laptop, cell phone, in-train network	Train carriage	User stationary, passing environment high-speed	Mobile messaging, video stream, conditional access	> 10 Mb/s	Real-time video
Trotwood	PDA, laptop, E-wallet, cell phone, auto-teller	In car and airport	Stationary and pedestrian walking	Voice, personal organizer, email, voice mail, map download	0.5 Mb/s	Voice, time to download map
Macawber	PDA, laptop, cell phone, video screen, in-plane network	Airport lounge, in plane	Stationary and walking	Email, word processing, spreadsheet, secure WLAN access	Up to 10 Mb/s	Transfer to small video screen
Gradrind	Cell phone, set-top box, home network, remote control, E-wallet	In home	Stationary and walking	Games, mobile	Low-rate messaging, ordering goods or services	None

TABLE 1. Example user scenarios for interworking of networks.

Key features	Bluetooth 802.15.1 ^a	802.15.3 ^b	802.15.3a UWB/HDRC ^c	802.15.4 ZigBee ^d
Status of standard	IEEE approved v. 1.1 (low rate)	IEEE approved	Under discussion	IEEE approved
Operating frequency	2.4–2.4835 GHz ISM band	2.4–2.4835 GHz ISM band	3.1–10.6 GHz	868–868.6 MHz (EU) 2.4–2.4835 GHz (ISM)
Maximum data Rate	1 Mb/s	11 Mb/s (QPSK)–55 Mb/s (64-QAM)	110 Mb/s (< 10 m) 200 Mb/s (4 m) 480 Mb/s (2 m)	250 kb/s, 40 kb/s, and 20 kb/s
Maximum range	10 m (opt. 100 m ^{**})	10 m	10 m	30m
Modulation	GFSK	D-QPSK or 16, 32, 64-QAM	BPSK, QPSK	BPSK, OPSK
Spreading	DS-FH	N/A	Multiband OFDM or direct sequence	DS-SS
Maximum transmit power	0 dBm ** Optional 20 dBm for 100 m	100 mW EIRP for EU (ETS 300–328)	–41.3 dBm/MHz 0.562 mW average EIRP/full band	20 mW (2 MHz channels @ 10 mW/MHz)
Cost	\$5	Unknown	Initially high (> \$20)	\$2.50

^a <http://www.bluetooth.com>

^b <http://www.ieee802.org/15/pub/TG3.html>

^c <http://www.ieee802.org/15/pub/TG3a.html>

^d <http://www.zigbee.com>

TABLE 2. Comparison of current PAN technologies.

example scenarios is wide. Thus, there is a clear requirement to ensure that the user only buys devices appropriate to his/her needs. Certainly, Gradrind would not want the extra cost associated with the high-rate applications, while users in the other scenarios would consider buying more expensive multimode devices that reduce the number of devices they need to carry. At the same time, devices of all capabilities must be able to communicate at some level if the goal of pervasive communications is to be achieved. Comparing these requirements to currently available solutions highlights that there are technological shortcomings that need to be addressed.

Given the user and technical requirements, it has been possible to identify the key technical challenges relating to wireless enablers; these are where currently the requirements cannot be achieved. The identified gaps in knowledge then form the program objectives.

Within the scope of the Mobile VCE research program, the objectives within this work area fall within two distinct classes:

- High-speed PANs to enable rapid transfer of data or content during brief periods when in the proximity of a suitable source
- Multistandard terminals that can handle simultaneous connections to the networks of multiple operators

The key research problems to be addressed for the high-speed PAN concept are summarized as:

- Identification of bandwidth-efficient transmission methods, as well as the potential utilization of higher frequencies
- Characterization of wireless channels for body-worn devices
- Improved methods of spectrum sharing (including interference mitigation) to accommodate both bursty and isochronous data types
- Adoption of low-cost low-volume power-efficient technical solutions

Additionally, for multistandard terminals the following problems will be appraised:

- Identification of architectures that allow a single silicon

implementation to demodulate multiple standards in a cost- and power-efficient way.

- Support of mobility in systems such as terrestrial DVB (DVB-T), where current implementations are unsuitable for handheld devices. More recently, the development of the DVB-H standard³ goes some way toward this objective.
- Methods and enablers for achieving simultaneous support of multiple bearers (e.g., orthogonal frequency-division multiplex, OFDM, based technologies for broadcast and WLAN; and 3G code-division multiple access, CDMA, technologies), as well as possible future developments of air interface standards.

The following two sections discuss how these technical challenges are being addressed.

Technologies for Personal Area Networks

Much of the work on PANs relies on having a good understanding of the radio channel characteristics. This is particularly true for body-worn devices, where, although mobility may be low, variation of path loss due to body shadowing and antenna orientation can be substantial with the radio paths between devices relying on reflected signals or interdevice routing to avoid the direct path through the body. Thus, channel characterization forms a critical activity. From this new knowledge, the design of efficient and resilient coding and modulation schemes (the air interface) can be appraised in order to make best use of the available channel.

Many PAN technologies are expected to operate in shared spectrum, and at the least a PAN will have to coexist with other PANs. In order to ensure reliable communications in shared environments, efficient medium access control (MAC) and radio resource management (RRM) algorithms need to be assessed in the PAN environment. Of primary concern is whether distributed or centralized algorithms are the best approach, balancing

³ <http://www.dvb.org/index.php?id=278>

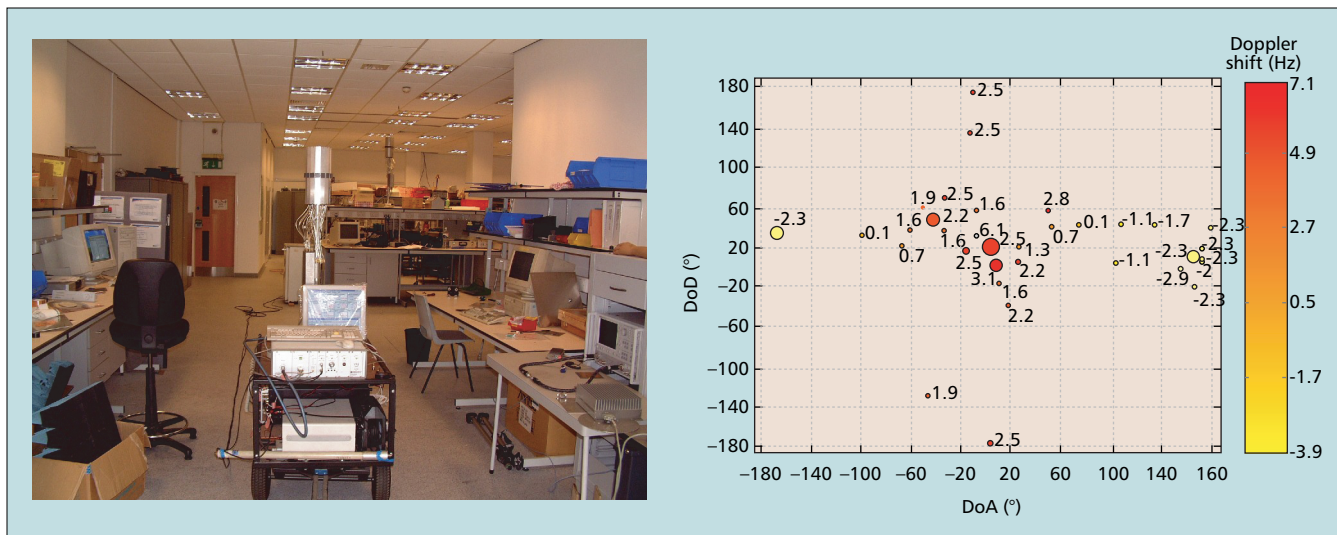


FIGURE 2. Experimental setup and results for indoor 5 GHz double-directional measurements.

spectrum efficiency and QoS requirements. However, providing any QoS assurance in shared spectrum is a significant challenge. The level of coordination between devices needs to be considered, for both within the same PAN and between different PANs. While higher levels of interaction can improve spectrum efficiency and provide better QoS integrity, the additional overheads and complexity may mean they are not suitable for this application. In most situations a degree of interference has to be accepted, so optimization of the air interface along with interference mitigation processing (in the temporal and spatial domains) must be considered. Interaction with the PDE work area will ensure that QoS provisioning can be managed and supported across protocol layers.

The Physical Layer for PANs

A number of standards already exist for PANs, with others still under development. A summary is given in Table 2. Comparing Tables 1 and 2, it is clear that for some applications existing technologies (Bluetooth & Zigbee) are not appropriate due to their low data rates. Also, too little is known about the performance of future technologies (IEEE 802.15.3 and 3a), particularly for body-worn networks, to be certain they can meet the requirements. For example, the frequencies used for ultra-wideband (UWB) systems have high propagation losses through obstructions, which is particularly pertinent for body-worn applications. The requirement for communication beyond just the body does not allow the use of electric field technologies [4].

A decision on the IEEE 802.15.3a standard has not been ratified, with the candidates being the Multi-Band OFDM Alliance and a direct sequence CDMA approach [5].

An alternative also under development is known as Wireless 1394 [6], which is a variant of the wired high-speed bus technology commercially known as FireWire (IEEE 1394). However, none of the Wireless 1394 initiatives define a new physical layer; instead, they are based on WLAN technology. While potentially meeting the capacity requirement, the cost and power consumption of such systems are an issue unlikely to be solved in the near term. Bluetooth is a good example of a design that has focused on low-cost design (using Gaussian frequency shift keying, GFSK, rather a more spectrally efficient air interface) to meet market requirements; however, market requirements have now moved on.

Air interface design is highly dependent on the channel. Characterization of peer-to-peer links is reasonably mature for conventional technologies, with European Telecommunications Standards Institute (ETSI) broadband radio access network (BRAN) publishing models for single- and multiple-antenna systems that are appropriate for WLAN applications [7]. Previous Mobile VCE research has measured the novel double-directional channel behavior for multiple-input multiple-output (MIMO) channels at 5 GHz, over bandwidths of up to 120 MHz [8]. Figure 2 shows the experimental configuration and the results of the double-directional analysis, relating direction of departure (DoD), direction of arrival (DoA), and Doppler shift for each multipath component. The size of each circle indicates the relative strength of each path gain.

While the benefits of MIMO are well understood, for PANs many devices need to be small and cheap. Consequently, the complexity of MIMO systems is not necessarily justified, and their use is being carefully considered. In addition, many devices are close to the body, and in some cases both ends of the link are body-worn (same or different body) and not necessarily in a good location from a transmission efficiency perspective (e.g., in pockets, bags, or even embedded into shoes).

To address the limited knowledge of channel characteristics for body-worn devices, a measurement campaign has been carried out. This has taken single antennas measurements in the 2, 2.4, and 5.2 GHz frequency bands, and in a number of environments (indoor, outdoor, small room, large room, etc.).

Device	Location	
Mobile phone	Next to head, right hand side	
Personal digital assistant	In chest pocket, right hand side	
Multi-mode terminal	Waist height, back pocket, left hand side	
Watch display	Around left wrist	
Location device	Around left ankle	
Personal computer	On a nearby desk	
Personal digital assistant	Next to nearby desk	

FIGURE 3. Location of antennas under consideration.

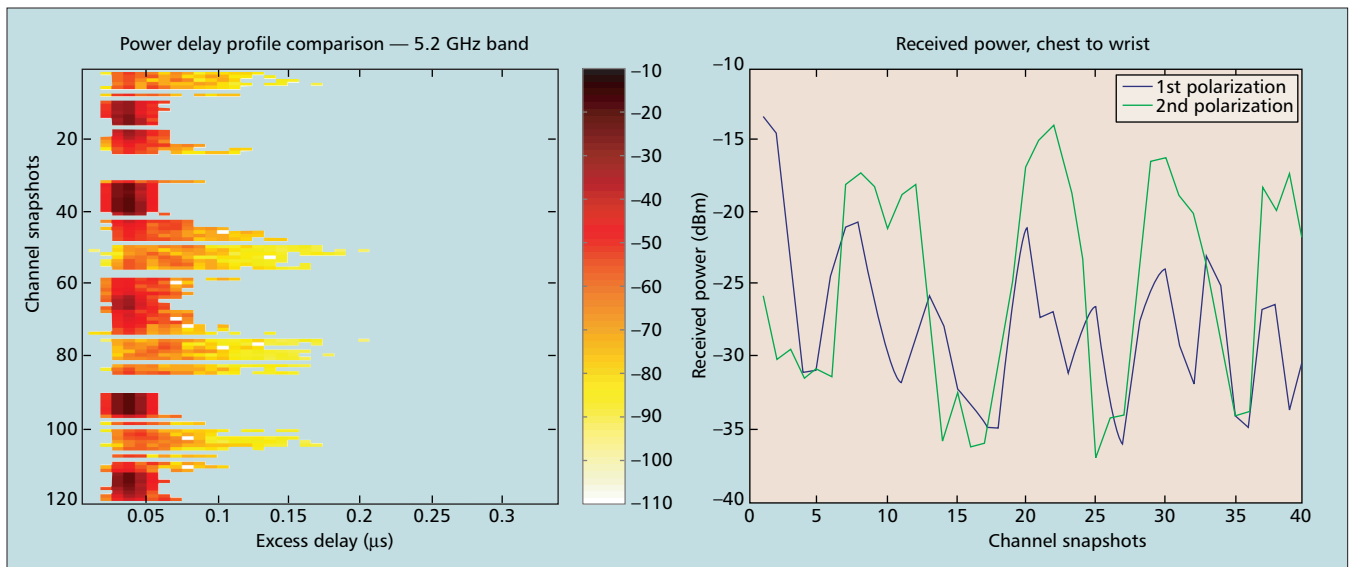


FIGURE 4. Power delay profiles and polarization time variation, chest to wrist, 5.2 GHz.

A number of antenna locations have been considered, as shown in Fig. 3, and the links between the different antennas characterized.

Power delay profile results (Fig. 4) show the large variation in delay spread and received power depending on the relative position of the transmitter and receiver, in this case due to the swinging of the arm with a wrist mounted device. In this case body blocking is seen to cause 15 to 25dB of signal loss. By using dual polar patch antennas, allowing simultaneous measurements on both polarizations, Fig. 4b also shows that while the variation is not due solely to polarization orientation, the difference in received signal strengths for the two polarizations could give worthwhile diversity advantage.

Figure 5 shows the difference in channel properties as a function of receiver location on the body and the environment. These all show similar trends, with high channel attenuations giving higher delay spreads, and lower K-factors.

Lower frequencies (2.4 GHz) show similar behavior, but with lower channel attenuations. The measurements have successfully demonstrated the relation between the user's actions and the channel characteristics. Analysis of the channels has shown that for on-body scenarios, there are clear distinctions between the channels depending on the presence or absence of a line of sight. Whether the user's body obstructs the link or not has been shown to be the dominating factor for the channel characteristics.

From the measured characteristics, what are the implications for the air interface? A number of questions now need to be answered. *Is an equalizer needed over such short links?* For symbol periods much greater than the maximum excess delay the answer is no, which applies for low to moderate data rates. However, this may not be the case when communication beyond the BAN is required and path lengths are longer. Also, for obstructed paths, the communication will rely on reflection from the local environment. *How much coding is needed?* Stronger codes give more reliable communication, but this needs to be traded against the complexity. *Due to variability, is power control sufficient, or does the air interface need to be adaptive to ensure that links can be maintained as the user goes through his/her usual routines?* The link budget requirements for the different applications and scenarios need to be determined, and then related to the regulations in each frequency band. Where a fixed air interface does not meet the requirements, an adaptive air interface will need to be

designed to better address the variability of the channel (Fig. 4b). When the link data rate is widely varying, buffering can smooth the flow, but at high rates and with slow variation (order of seconds) the size of the buffer to have a useful effect becomes an issue.

Where there is still insufficient link budget (either from path losses or due to interference) there is a need to consider physical layer link enhancement methods such as exploiting the spatial channel and time-domain-based interference mitigation. Any solution will need to carefully address benefits vs. cost. The work program will consider the interactions between the protocol layers and put the mitigation at the appropriate level. For example, rather than deploy diversity antennas and include strong coding, it may be better to have multiple hops controlled by the network layer that go round an obstruction, rather than try to go through it at the physical layer. The mitigation method may need to be chosen adaptively based on the network configuration (arrangement of devices locally) and the capabilities of individual devices (processing capability and availability of multiple antennas). Ideally, crosslayer interaction can be used to find the optimum mix of processing and protocols to meet the system requirements, given the channel conditions.

MAC and RRM

The best way to mitigate interference is to avoid it in the first place, since the ability to mitigate it at the physical layer is limited. This process is under the control of the data link layer, which can be subdivided into the RRM and MAC. The division of importance between the two processes is system-dependent, and within this project the balance of power can change. It is envisioned to split the operation mode into basic and enhanced modes of operation (Fig. 6). For basic mode devices, where there is limited processing power and distributed management, most of the interference avoidance will occur within the MAC, since a local RRM process (if any) will have limited capabilities (thin RRM), placing more emphasis on channel-contention-based access. However, in enhanced mode, where a more capable device can take control of the PAN (or even multiple collocated PANs), there is a greater ability to optimize the radio resources over the local area, reducing the reliance on the MAC to control interference (thin MAC). The concept of *basic* and *enhanced* modes fits well within the spheres of influence defined by the Wireless World Research Forum (WWRF), shown in

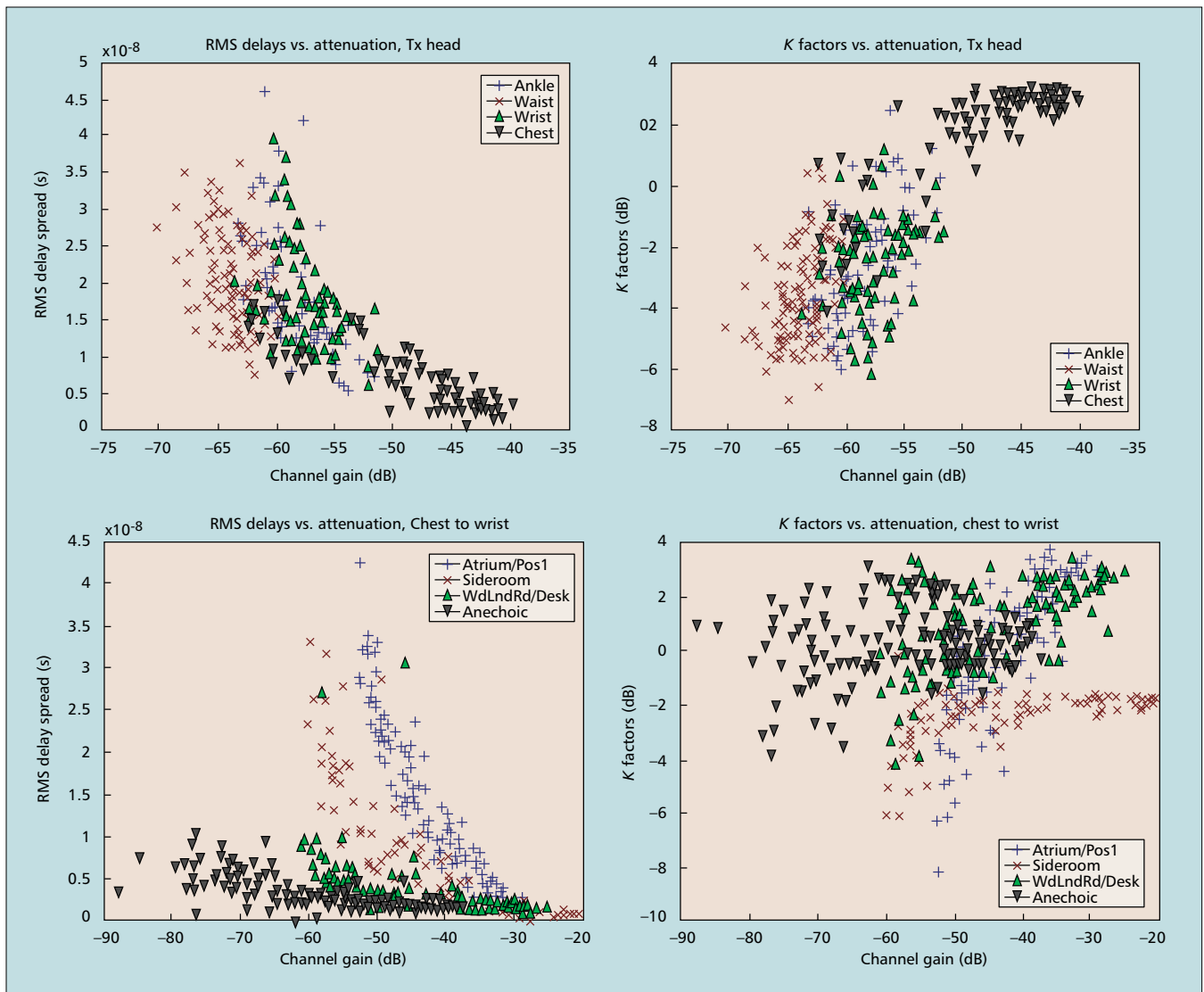


FIGURE 5. Comparison of RIVIS delay spread and K-factor for different receiver body locations (transmitter on head, small room) and for different environments (chest to wrist path), 5.2GHz.

Fig. 7. Basic mode devices are typically body-worn (BAN/PAN), and power consumption, weight, and size are very important to the user. Enhanced mode devices, in the immediate environment or instant partners, are more typically fixed (or portable) and may connect to a main power supply, so there are fewer physical constraints than for the body-worn devices.

Past work has been more focused on resource management for the wide area, and where interference is mostly under the operators' control. Typically, the flow of information is strongly from the networking layer down to the physical layer. An important process in RRM is determining a QoS metric (e.g., required bit error rate, BER, and latency), or resource management estimator (RME), and then relating this to a resource allocation strategy. The measurement of the QoS metric is a key process, timeliness and accuracy of this measure is essential to allow the RRM to work effectively. For example, while measured BER derived from the higher protocol layer, can be used, the accuracy of this measure is debatable over short measurement timescales, but measurements over long intervals do not adequately track instantaneous conditions on a packet-by-packet basis. Measuring the signal-to-interference ratio mean and variance over short intervals, and then mapping these onto a BER figure, the radio resource mapping

function (RRMF), is proposed [9]. This requires the flow of information from the physical layer to the RRM. Further, in dynamic environments predictive RME processes can further improve performance [9].

What are the requirements for the MAC and RRM specific to the PAN? Those identified by this project include:

- Ad hoc network support, since no fixed infrastructure can be assumed
- Seamless and quick integration of devices into the PAN — long setup times lead to lost opportunities
- Adaptive and flexible throughput to support the range of requirements as demonstrated in Table 1
- Support delay-sensitive traffic (e.g., video and audio)
- Support message prioritization (through the MAC)
- Fairness of access and polite policies such that one device cannot monopolize the radio resources (inter- and intra-PAN issues)
- Network scalability in order to support a large number of devices (a problem with Bluetooth)
- Robustness to other collocated systems, particularly where there is no coordination
- Support of dynamic service and feature availability

It is clear that existing data link layer (DLL) protocols fall short of many items on this list of requirements, particularly

in provision of QoS management in unregulated spectrum. It is the objective of this program to develop the required MAC and RRM protocols that meet the requirements as closely as possible. Where QoS requirements cannot be met, this will be signaled to the PDE to determine the course of action required.

A basic choice exists between centralized and distributed management protocols. A centralized RRM provides a better view of the traffic conditions and maximum sustainable interference (MSI) for different terminals, so a better allocation of resources could be expected. However, this would require additional signaling from participating terminals. Alternatively, a distributed algorithm might suit the ad hoc nature of the network, and local information will be more easily available (e.g., channel state information). However, collection of information will not be central, and information about resource usage will require additional signaling or intelligent resource selection schemes.

The DLL architecture adopted by the Mobile VCE for this application is based on the WHYLESS.COM architecture,⁴ but with some modifications to better suit the QoS requirements (Fig. 8). The basic split of the DLL is the radio resource controller (RRC) and the RLC/MAC layer, or alternatively the control plane and the user plane. Whereas the WHYLESS.COM approach divides data traffic into two classes according to QoS or non-QoS guarantee requirements, the Mobile VCE approach defines time-constrained resources and dynamic resources:

- **Time-constrained resources (TCR)** include all QoS requirements that are restricted by a time constraint. TCR can only be handled and negotiated via the network layer; however, allocation does take place in the MAC layer.
- **Dynamic resources (DR)** are entirely handled in the MAC layer and are used for limited QoS effort communications without time constraints. The resource can vary as quickly as on a per-packet basis. The DR includes all other QoS and non-QoS transmissions.

The multiple access (MA) scheme in use will determine which resources are available, so the MA scheme needs to be designed based on the joint requirements of the physical layer and DLL. Furthermore, in operation this interaction continues and must be exploited to optimize system performance. This requirement for cross-layer interaction is explicitly shown in Fig. 8.

A final issue requiring consideration is the timescales over which the control processes operate. The RRM typically operates over slow timescales (e.g., per call), whereas the MAC can respond more quickly on a per-packet basis. However, for the dynamic PAN environment, and the wide variation in QoS requirements, there may be a need for resource allocation to operate more quickly than has previously been the case. Extensions to the work on the RME and RRMF will require these to operate over much shorter timescales than WANs to match the expected greater dynamic behavior of PAN environment (interference environment and device associations). However, for ideal optimizations the RME information may need to be shared between devices, which has implications for the PAN architecture and may only be possible for enhanced modes of operation.

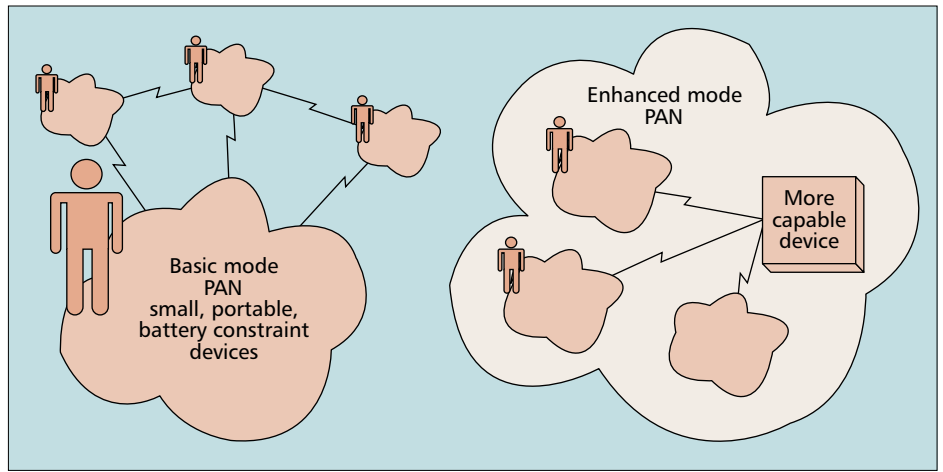


FIGURE 6. Illustration of basic and enhanced modes of operation.

Technologies for Multistandard Terminals

Where multiple standards are to be supported, a common architecture that allows the sharing of hardware resources between standards will lead to cost and power consumption minimization. Aspects to be considered are the sampling architecture to allow the use of a common clock (with appropriate sample rate conversions for each network), time scheduling of resources such as fast Fourier transform (FFT) processors or decoders, and common synchronization processes. Additionally, new concepts in linearized power-efficient amplifier design need to be investigated to support the increased linearity requirements for multiple concurrent transmissions, where due to the co-located nature of transmit and receive signals the impact of poor adjacent channel emissions or harmonic spurious responses are more critical.

Terminals will only have finite resources, and different users will have different terminal capabilities. Interaction with

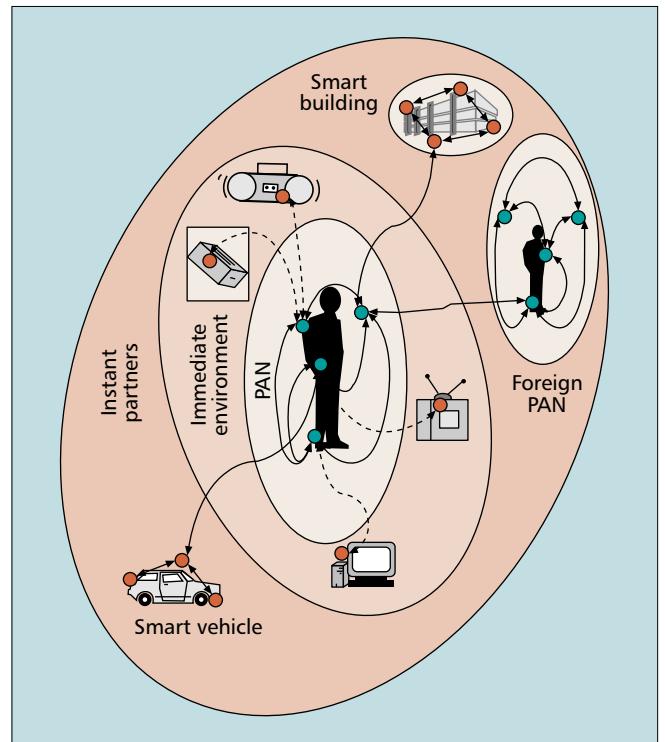


FIGURE 7. Spheres of influence surrounding the user. (WWRF, Book of Visions 2001, http://www.wireless-world-research.org/general_info/BoV2001-final.pdf).

⁴ <http://whyless.org>

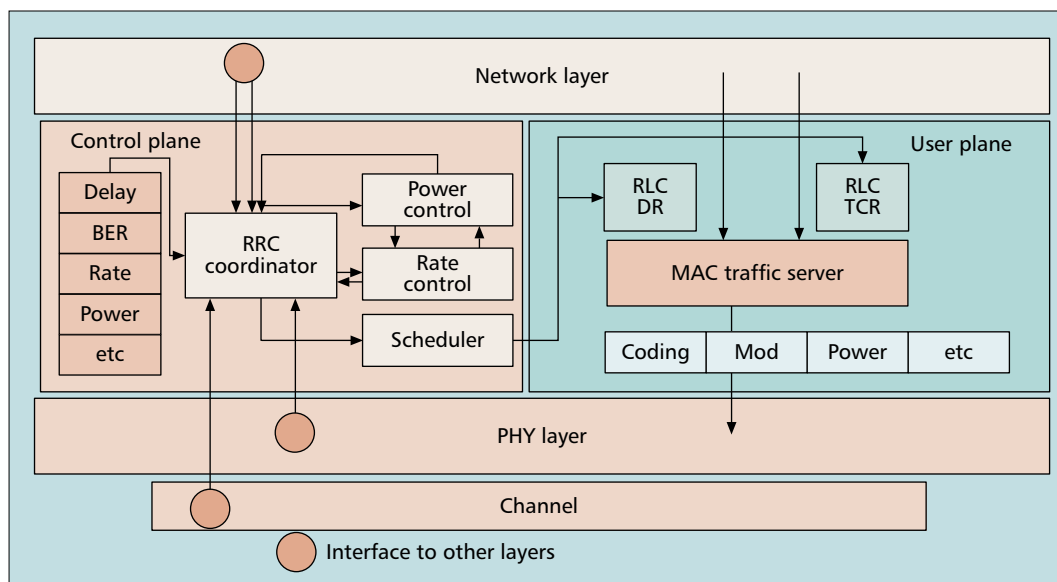


FIGURE 8. Mobile VCE PAN DLL architecture.

the PDE work area will ensure the feature discovery protocol is aware of terminal hardware capabilities (e.g., FFT symbol rate and buffer size) and the associated QoS limitations (e.g., limited support for real-time applications) such that only services (or mixes of services) that can be supported by the available hardware can be requested.

While much of this research program considers interworking with existing air interface standards, some of the work considers how these may be extended using new multichannel and multi-antenna concepts, while still allowing existence within the common terminal architecture.

Architectures for Multistandard Terminals

It is the purpose of this project to enable a multimode terminal to communicate over a number of standards and networks, according to network availability and user preferences. The term *multimode* is distinct from software-defined radio, in that it is not anticipated that the radio will be reconfigurable outside a limited set of standards. The focus is to build a terminal that can be implemented with minimum complexity, taking advantage of any commonality in standards definition and processing requirements, such that complexity grows more slowly than linearly with the number of standards implemented. To be more precise, Table 3 shows the standards to be considered within this project; note that the cellular, WLAN, and broadcast industries are represented.

In the user terminal, the receive segment needs to be able to process all the listed standards, whereas on transmit only the WLAN and cellular standards need to be supported. The obvious commonalities are the repeated use of OFDM, and the common mother convolutional code for the broadcast and WLAN systems. Before going further, the definition of *simultaneous* operation needs consideration. At one extreme is completely simultaneous, where there are no restrictions on the operation of any standard. However, the ability to share hardware resources to reduce complexity is limited. At the other extreme is standard switching, where the terminal can support all the required standards, but only one at a time. This latter option has the disadvantages of requiring resynchronization to the network at every switching, and any paging messages could be lost if the terminal is not listening to the right network at the right time. A compromise between the two is to maintain synchronization to each network and decode only the management data, unless it is known that application data is arriving. For example, in digital audio

broadcast (DAB), only the null, synchronization, and fast information channels need decoding most of the time, and the main service channel is decoded only when necessary. For this example, when there is no data to download a duty cycle of only 5:77 is required for DAB. The time slicing of DVB-H can also be similarly exploited.

Hardware resources at the terminal can be shared between networks, and the duty cycle of transmissions can be exploited to minimize complexity. However, such gains may only be statistical, and methods need to be implemented to deal with situations when the instantaneous demand on a resource is higher than it can provide, such as the processing rate of an FFT processor when multiple services with real-time QoS requirements are being delivered. Buffering can be used in the digital subsystems to alleviate the problem, but buffering will also only have finite capability and will adversely affect any latency QoS requirements. To prevent overload situations arising in the first place, the data delivery traffic to the terminal should be managed. This can be achieved by the PDE being aware of the terminal capabilities (e.g., FFT processing rate and buffer size) and shaping the traffic flow within those constraints.

With the requirement of frequency domain processing for the OFDM waveforms, how to use frequency domain processing for CDMA is also being considered. Examples include extension of work on chip-level equalization into the frequency domain, and frequency domain synchronization for CDMA. Such dual-domain processing enables the aim of adding the capability of more standards, but without a proportional increase in cost and volume of the terminal. Efficient hardware architectures for FFT processing with different transform lengths also need careful consideration. *Is a small butterfly structure used repeatedly for large FFTs, or is a large butterfly partitioned to allow parallel FFT processing for shorter blocks?* Terminals with both solutions could coexist.

Generally, different chip/sample/data/symbol rates are specified in different standards. A primary concern is sample rate conversion, which needs to be efficient because one conversion for each network is required, since no intersystem synchronization can be assumed. The obvious simple solution is to adopt a different dedicated clock for each network. However, this is inefficient. An elegant solution to this is to provide different processing rates for different standards by means of digital sample rate conversion (SRC) with only one fixed clock. Only one clock is needed, and the number of analog-to-digital converters (ADCs) can be reduced to the minimum.

Property	3G WCDMA ^a	DVB-T ^b	DAB ^c	IEEE 802.11a ^d
Format	CDMA	OFDM	OFDM	OFDM
Frequency range (United Kingdom)	FDD — 1920–1980 and 2110–2170 MHz, paired TDD — 1900–1920 and 2010–2025 MHz, unpaired	VHF 174–238 MHz UHF 470–682 MHz	Band III (UK) 217.5–230 MHz L-Band 1452–1492 MHz	Indoor 5150–5350 MHz Both in/outdoor 5470–5725 MHz
Channel bandwidth	5 MHz	6, 7, 8 MHz	1.536 MHz	20 MHz
Data rates	12.2kb/s–2 Mb/s	Fixed transmission 5 to 32 Mb/s Mobile transmission 5 to 15 Mb/s	8 to 384 kb/s for audio broadcast (BBC etc.) 1.5 Mb/s in a complete “ensemble”	6 to 54 Mb/s varied due to different modulation scheme
Modulation	QPSK	QPSK, 16 QAM, 64 QAM	DQPSK	BPSK, QPSK, 16 QAM, 64 QAM
Carriers	Single carrier	2k mode 1705 carriers 8k mode 6817 carriers	Mode I 1536 carriers Mode II 384 carriers Mode III 1192 carriers Mode IV 768 carriers	52
Duplexing	FDD and TDD	N/A	N/A	CSMA/CA
Spreading	Variable 4–512 3.84 Mcips/s	None	None	None
Inner code	Convolutional (K = 9, rate 1/2, 1/3) Or Turbo (8-state PCCC, rate 1/3)	Convolutional (K = 7, rates 1/2–7/8 with puncturing)	Convolutional (K = 7, rates 8/9 – 8/32 with puncturing)	Convolutional (K = 7, rates 1/2–3/4 with puncturing)
Outer code	CRC	RS(188,204,8)	None	CRC

^a 3GPP Radio Specifications, <http://www.3gpp.org>.

^b ETSI EN 300 744 v1.4.1 (2001-01), “Digital Video Broadcasting (DVB); Framing Structure, Channel Coding and Modulation for Digital Terrestrial Television,” 2001.

^c ETSI EN 300 401 v1.3.3 (2001-05), “Radio Broadcasting Systems; Digital Audio Broadcasting (DAB) to Mobile, Portable and Fixed Receivers,” 2001.

^d IEEE Std 802.11a-1999, Part II: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: High Speed Physical Layer in the 5 GHz Band.” Note that while IEEE 802.11a is listed, the physical layer of HiperLan2 [10] is very similar, so the discussion is applicable to that standard as well.

TABLE 3. Standards for a multimode terminal.

However, the sample rate needs to be minimized to keep power consumption low. Because the sampling rate of IEEE 802.11a is the highest among the sampling rates of the standards considered, a possible solution for this sampling rate conversion problem might be based on oversampling for WLAN, with clock timing alignment for that system, and then approximating sampling data or sampling instants for CDMA, DAB, and DVB-T.

Taking the base clock rate as multiples of 20 MHz, Fig. 9 shows that for the DVB system a 40 MHz clock rate with linear interpolation can provide near ideal timing alignment. Since the other standards have lower sample rate requirements than DVB-T, 40 MHz is a good initial choice.

It is important to integrate synchronization into the architecture. As previously discussed, maintaining network synchronization allows rapid switching between data delivery mechanisms, but to do this efficiently requires acquisition and tracking not relying on data demodulation. For OFDM applications this essentially means pre-FFT synchronization, exploiting the structure of the signal, most commonly the repetition associated with the cyclic prefix. In order to enhance the ability to support mobile operation, rapid acquisition techniques are required. Further difficulties relate to the multipath environment, which is more challenging when single-frequency networks are to be accommodated.

Previous research on cyclic prefix processing for synchronization performs poorly when the channel impulse response is significant across a large part of the prefix, so a greater prefix length has been required for synchronization purposes. Averaging synchronization estimates over a number of symbols improves performance in slow moving channels, but this limits mobility. Consequently, more accurate “one shot” estimators will enhance the ability to support greater mobility. Furthermore, for burst-based standards such as WLAN, synchronization on a per-packet basis is essential.

Efficient RF Processing

In the transmitter segment of a multimode terminal, the principle problems lie in the analog radio frequency (RF) processing due to the range of center frequencies, channel bandwidths, and the linearity required by higher-order and multicarrier modulation schemes. The spurious emissions of a transmitter become more critical when multiple standards are supported within a single device. Even if the transmissions meet the requirements defined by the standard specification, the spurious signals could still have an adverse effect on collocated receivers. Furthermore, when simultaneous transmissions from the different standards are required, there is an increased likelihood that harmonic or intermodulation distortion will fall within the bandwidth of one of the receive chan-

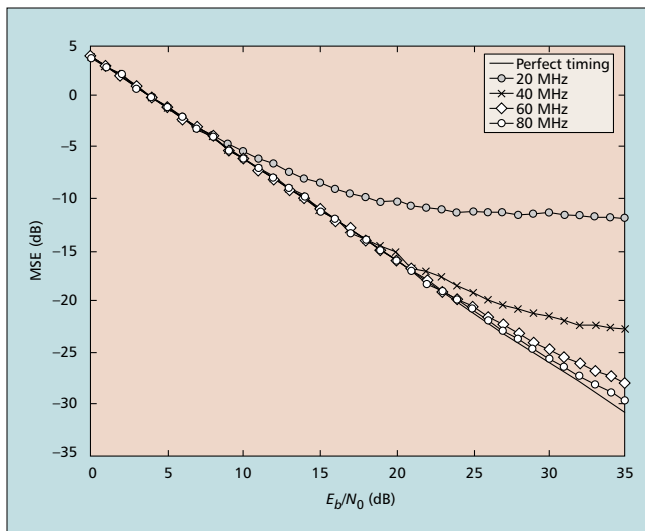


FIGURE 9. Performance of different sampling rates for DVB-T with interpolation (MSE is mean square error of data signal).

nels. If one or more of the standards allows flexibility in when packets/data are transmitted, transmit scheduling can be used, but this is not always possible.

Highly linear amplifiers, such as using backed-off class-A mode, often have power efficiency penalties, so architectures that combine linearity and efficiency are required. Table 4 shows a comparison of the achievable linearity and efficiency of conventional amplifier solutions. A common solution is to use an efficient but nonlinear power amplifier and apply linearization techniques to meet the spurious requirements. Two approaches being considered are piecewise linear predistortion (PLP), and envelope elimination and restoration (EE&R). The former is a feedback method that can provide enhancements in linearity, as demonstrated in Fig. 10. However, the benefit is more limited when the envelope variation is significant, such as for multicarrier and high-order modulation techniques. PLP on its own cannot sufficiently linearize an efficient amplifier (such as classes C or E). The EE&R technique is more suitable for greater envelope variation, but requires additional processing to meet the linearity requirements. The architecture in Fig. 11 combines the two methods in order to meet both linearity and efficiency requirements.

Exploiting MC-CDMA Air Interfaces

From Table 3 it is clear that the air interfaces for data delivery mechanisms fall into the CDMA or OFDM class. CDMA has the advantages of exploiting frequency diversity, and allows for better frequency reuse in cellular systems and consequently easier network planning. OFDM uses equalization in the frequency domain for low complexity, allows water filling processes to be employed (e.g., bit loading or power con-

trol per subcarrier) to maximize capacity subject to practical constraints, and by exploiting the cyclic prefix allows for the implementation of single-frequency networks. Theoretic performances of multicarrier (MC) and non-MC techniques are equivalent to a single user transmission, but in practice the implementation will lead to differences (e.g., OFDM cannot fully exploit multipath in practice).

The MC-CDMA approach aims to combine the advantages of these two technologies. With additional degrees of freedom, the air interface can be adapted to optimize performance over the channel conditions. This is much in line with other thinking on 4G systems, such as NTT DoCoMo VSF-OFCDM [11]. There are different approaches to MC-CDMA, relating to whether the spreading aspect occurs in the time or frequency domains. The MC-CDMA approach can be applied to single- and multi-user cases. In the single-user case all subcarriers are used, and the CDMA mechanism allows multi-code transmissions, which can provide diversity in the time and frequency domains. For multi-user systems, the multiple access mechanism can be based around spread code allocation (CDMA), subcarrier allocations (OFDMA), or even some hybrid approach.

MC-CDMA includes the current broadcast, cellular, and WLAN technologies as special cases. Consequently, a multi-standard terminal that can operate over the range of MC-CDMA parameters, such as scalable spreading code length and number of subcarriers, would be able to support many current and future air interface standards. For this goal to be achieved the scalability of different algorithms to different parameters needs to be assessed. In particular, how scalable are different algorithms to spreading factors (such as 1–512) and number of carriers (1–8192)? Algorithms that need consideration include frequency domain chip equalization, multi-user detection (MUD) suitable for range of spread factors and MC configurations, synchronization issues, and channel estimation.

As well as scaling according to the air interface parameters, the processing algorithms should ideally be scalable around the computational complexity a terminal can support. In a multistandard terminal the available computing power to one network thread may fluctuate based on the needs and priorities of the other active networks. Iterative processing algorithms (e.g., turbo codes) allow a coarse computational adjustment based on the number of iterations. Iterative techniques have also been applied to MUD algorithms, but the complexity of even a single iteration can be significant, such as for maximum likelihood (ML) processing. New approaches based on genetic algorithms (GAs) have been developed, in which a single iteration is a small number of simple computations. With a sufficiently large number of iterations, ML performance can be approached at much lower complexity. The GA approach also offers very fine granularity over controlling

	Power added efficiency	Adjacent channel protection ratio	Supported access schemes	Peak to average power ratio
Class AB (typical product specification)	16%	–45 dBc	W-CDMA	8 dB
Class A (simulation without linearization schemes)	< 10%	–35dBc	OFDM	12–15 dB
Class C with PLP (simulation)	47%	–37 ~ –22 dBc	OFDM	12–15 dB

TABLE 4. Comparison of efficiency and linearity for different amplifiers.

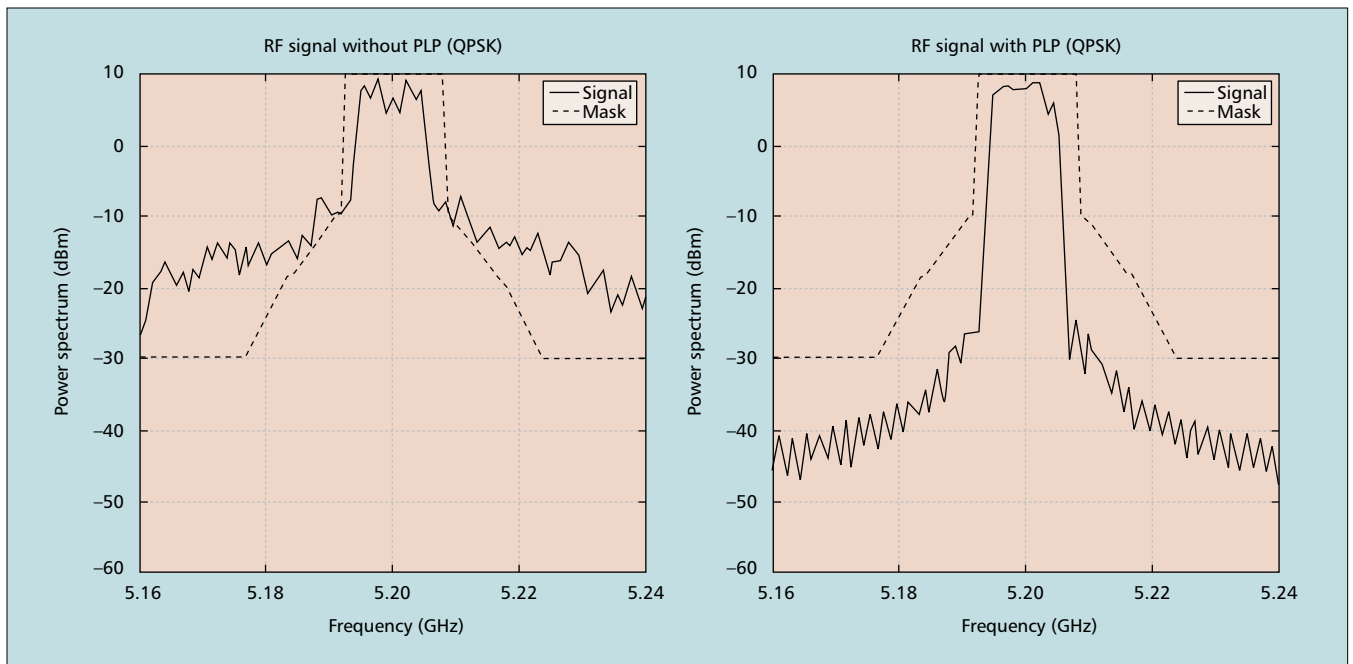


FIGURE 10. Demonstration of performance enhancement using PLP (802.11a spectrum mask, class C power amplifier).

the complexity of the MUD process, providing a good degree of scaling as required.

Conclusions

A multifaceted research program has been described to support the physical and data link layer aspects of the interworking of networks concept as part of the Mobile VCE research program. Two broad topics are addressed: PAN technologies for interference dominated environments, and multimode terminal architectures and technologies. The physical and data link layer activities will maintain close links with the two other work areas within the Mobile VCE program (IoN and PDE) to ensure cross-layer interactions maximize performance and QoS provision.

For PANs, key issues are understanding the channel characteristics of body-worn devices and making the best use of the available spectrum, while also being robust to interference from other devices (most PANs are expected to operate in shared spectrum with limited intersystem coordination).

RRM for PANs needs to be reconsidered given the different environment in which they are expected to operate compared to WANs. Key differences in requirements include network topology dynamics, wide variation in QoS requirements, channel variability, operation in uncoordinated spectrum, and RRM implemented in small cheap devices. It is proposed to consider two modes of operation, a basic mode for low-cost devices and an enhanced mode when more capable devices are available to carry out more complex resource allocation optimization and coordination.

It is important to provide an appropriate compromise between complexity, performance, and cost, where different devices will have different configurations due to differing constraints. Thus, multimode terminal architectures need to be sufficiently flexible to deal with this, and synchronization needs to be considered an inherent part of the architecture. MC-CDMA provides a framework not only for existing standards but also for future evolutions (beyond 3G, 4G, etc.). The need for scalability of processing to cater for different air

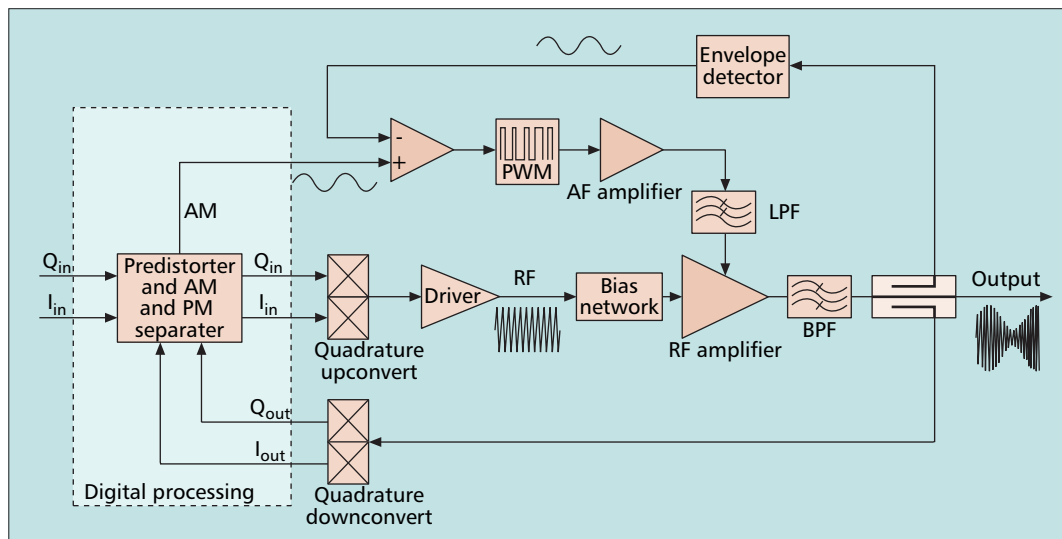


FIGURE 11. Combined PLP and EE&R architecture.

interface parameters and time-varying availability of processing resources has been discussed. Other issues being addressed include linearized amplifiers to support the high peak to mean signals generated by multicarrier and CDMA air interfaces.

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Biographies

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